Where does S-wave energy on OBC recordings come from?

Carlos Rodriguez-Suarez1,2*, Robert R. Stewart2, and Gary F. Margrave2
1PETROBRAS-Petroleo Brasileiro S.A.; 2CREWES-The Consortium for Research in Elastic Wave Exploration Seismology, University of Calgary

Summary

A study of wave-mode conversion that occurs at the sea floor for downgoing seismic energy and a comparison with reflected conversions at a representative interface of Tertiary sediments is presented. To investigate if the presence of S-waves on the vertical component (and P-wave in horizontal) could be due to mode conversion close to the receivers, conversion for up-going seismic energy in the shallow sediments is also analyzed. It is concluded that: 1) most P- to -S conversion occurs as reflection at sediment interfaces, not at the sea-bottom, and 2) negligible mode-conversion (both P- to -S and S- to -P) occurs for the up-going seismic energy in the sediments and at the sea bottom.

Mode conversion for down-going wavefields

P- to -S mode conversion upon transmission of downgoing waves through the sea bottom may be important for hard bottoms (Vp>2500 m/s, Vs>1000 m/s), as the critical angle for the P-wave can be relatively small, generating most downgoing energy as S-waves (Tatham and Stoffa, 1976). According to Amundsen et al. (1999), the most important elastic parameter for the PS-SP mode (P converting to downgoing S at sea-bottom, reflecting as upgoing S and converting back to P at the sea bottom) is Vs just below sea bottom. As an example, the authors say that if a Vp/Vs ratio equal or lower than 3.0 occurs in these sediments, PS-SP amplitudes are comparable to P-P reflection amplitudes. However, most measurements presented in the literature (e.g. Hovem et al., 1991; Rodriguez-Suarez and Stewart, 2000) – at different locations, lithologies and water depths around the world – indicate that Vp/Vs is usually over 5.0 for these sediments. In addition, most reports on OBC data processing conclude that S-wave energy recorded at sea bottom is generated from P- to -S conversion at layer interfaces rather than at the sea bottom. In general, these conclusions came from moveout velocity analysis (the velocities are higher than expected from pure S-S mode) and/or poor imaging when conventional CDP processing is applied to horizontal geophone components. For these reasons, converted-wave algorithms – P-S velocity analysis, P-S DMO, P-S imaging, etc. – have to be used.

Mode conversions at a soft sea bottom and at a typical top Tertiary reservoir interface were analyzed and compared using Zoeppritz equations coded in Matlab at CREWES. The near ocean bottom sediments elastic parameters were obtained by averaging the data from Hamilton (1976, 1979), Baldwin et al. (1991), Breeding et al. (1991), Briggs (1991), Lavoie and Anderson (1991), Richardson et al. (1991), Theilen and Pecher (1991), Duennibier and Sutton (1995), Esteves (1996), Ayres and Theilen (1999), and Rodriguez-Suarez and Stewart (2000). The sea-bottom elastic parameters were obtained by averaging the upper five metres of sediments. Vp was obtained from Hamilton’s (1976,1979) expressions for siliciclastics. Table 1 shows the parameters used.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Vp (m/s)</th>
<th>Vs (m/s)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1500</td>
<td>0</td>
<td>1.05</td>
</tr>
<tr>
<td>Sediment</td>
<td>1515</td>
<td>100</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Table 1 - Elastic parameters for water and shallow marine sediments.

For a downgoing compressional wave at the sea bottom, Fig. 1 shows that, for most incidence angles commonly present in seismic acquisition, transmitted PP energy is more than 100 times higher than PS energy. This is a strong indication that P- to -S conversion at the sea bottom is small in many marine environments.

![Fig. 1 – Transmission coefficients for down-going PP (dashed) and PS (continuous) seismic waves in a sea/sediment interface (Table 1). Energy (proportional to square of amplitude) for PP is more than 100 times larger than for PS.](image)

For the reservoir / overburden interface, values normally found in unconsolidated turbidites sandstones of Tertiary age were used (Table 2). For these reservoirs the P-wave velocity contrast can be much higher than that for the S-wave. Generally, the density contrast is very large and cannot be neglected in modeling studies. Reflection coefficients for incident P- and S- waves at the top of the turbidite reservoir are presented in Fig. 2. P-S and S-S modes are of relatively similar values over most
incidence angles. No specific mode seismic energy is dramatically stronger than another for reflections at this interface.

<table>
<thead>
<tr>
<th>Layer</th>
<th>V_P (m/s)</th>
<th>V_S (m/s)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden</td>
<td>2800</td>
<td>1165</td>
<td>2.4</td>
</tr>
<tr>
<td>Reservoir</td>
<td>2530</td>
<td>1070</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 2 - Elastic parameters for reservoir (turbidite) and overburden Tertiary rocks.

The next step is to multiply the PS transmission coefficient at the sea bottom by the S-S reflection coefficient at reservoir top and compare the result with the product of PP transmission coefficient at the sea bottom by the P-S reflection at reservoir top. In other words, compare amplitudes of PS-S and PP-S modes. The results, shown in Fig. 3, indicate that most shear-wave energy travelling upward is created by the PP-S mode instead of PS-S mode. The figure also shows it may be necessary to have fairly large incidence angles to generate maximum converted-wave energy.

Comparison of PP-S energy to PS-S energy is given in Fig. 4 as a ratio. The values of PP-S energy over PS-S energy were clipped arbitrarily at 500 because the ratio values become very large around 25° as PS-S values tend to zero. One can see from Fig. 4 that PP-S energy is, in general, over 100 times stronger than PS-S energy.

Possible mode conversions (both P- to S- and S- to P-) in the up-going seismic energy were also analyzed. This test was to investigate a phenomenon sometimes observed in OBC data processing (Ebrom et al., 1998; Yuan et al., 1998; Li and Yuan, 1999; Rodriguez-Suarez et al., 2000): the presence of shear-wave energy on the vertical component while the radial component does not present compressional energy. Perhaps S-wave energy present in the vertical component could be due to some compressional energy converted from shear at shallow sediments, or at the sea bottom. If this is the case, the apparent P-P energy will have P-S behavior (e.g., P-S velocities and traveltimes).

The analyses done here are assuming perfectly elastic media. If a very low shear quality factor (Q_S) occurs in shallow marine sediments, different results from the ones presented here might be expected using anelastic modeling. However, published data (e.g., Hovem et al., 1991), suggests Q_S values below 10 are uncommon – in general, Q_S equals one half of Q_P in these sediments.

The interfaces analyzed for mode conversion were defined based on density discontinuities outlined by Rodriguez-Suarez and Stewart (2000). Main boundaries were observed at 5, 20, 92, and 163 m depth (Fig. 5). The resulting transmission coefficients for mode conversion (P- to S- and S- to P-) of the up-going wavefield are shown in Fig. 6 to 8.
S-wave energy on OBC recordings

Fig. 5 – Elastic parameters used in up-going mode conversion analyses (after Rodriguez-Suarez and Stewart, 2000).

It is clear in all pictures that the conversion is negligible at all depths, including the sea bottom, and that most energy transmitted through the interfaces corresponds to the same mode of the incident energy. For the up-going wavefield, the large contrast generally present between \( V_s \) in the incident medium and \( V_p \) in the transmitted medium causes a small critical angle for the SP mode, contributing to a small S- to -P conversion. Evanescent (interface) – or more complicated – waves generated at the sea-bottom from S- to -P conversion beyond the critical angle might be recorded on horizontal components of geophones. These waves would appear as PP-S events in seismic sections.

The presence of P-S energy on the vertical geophone component when little P-P energy occurs on horizontal components is somewhat of a puzzle. Additional analyses (PS-P mode or more complex mode conversion at very shallow sediments, like up-going S- reflected down as S- at the sea bottom, then reflected up as P-) indicate that, although possible, further mode conversions are unlikely to cause this phenomenon. Perhaps the shear-wave arrival is coupling onto the vertical geophone due to the mechanical instabilities of the cable and geophone system. Li and Yuan (1999) also considered this possibility. In some areas, reflection and/or scattering from out of the source-receiver vertical plane (sagittal plane) might contribute to this phenomenon.

Conclusions

Analyses of transmission and reflection coefficients for compressional- and shear-wave mode conversion using Zoeppritz equations were performed for both sea bottom and a typical hydrocarbon reservoir top of Tertiary age. It was concluded that most S-wave reflection energy recorded on the ocean floor by OBC is related to upcoming energy converted on reflection at an interface at depth and not from a downgoing shear conversion at the ocean floor. It was also concluded that, using elastic assumptions, mode conversion (both P- to -S and S- to -P) of the up-going energy is negligible in the shallow (above 160 m) sediments and at the sea-bottom.

Acknowledgements

We thank CREWES sponsors for their support. The first author thanks Petrobras for economical assistance in his research.

References


Briggs, K.B., 1991, Comparison of measured compressional and shear wave velocity values with predictions from Biot theory: Shear Waves in Marine Sediments, eds. J.M. Hovem et al., pages 121-130.


S-wave energy on OBC recordings

**International SEG Meeting.**


**Fig. 6 – Transmission coefficients for up-going P-wave (PP dashed and PS solid) at (from top to bottom) interfaces located at 5, 20, 92, and 160 m depth. Most energy does not suffer mode conversion.**

**Fig. 7 – Transmission coefficients for up-going S- and P-waves at the sea-bottom (PP dashed, SP continuous).**

**Fig. 8 – Transmission coefficients for up-going S-wave (SS dashed and SP continuous) at (from top to bottom) interfaces located at 5, 20, 92, and 160 m depth. Most energy does not suffer mode conversion.**